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A new type of large scale thermal energy storage

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Abstract

A new type of thermal energy storage (TES) with wide potential for renewable energy sources as well as conventional energy sources will be presented. The main energy storage medium is a special type of concrete that has significantly higher thermal conductivity than normal concrete. Although the recipe of this material is quite complex the main component is quartzite, a natural geo-material readily available in many parts of the world. Further, heat is transported in and out of the storage by way of a heat transfer fluid (HTF) which flows through steel pipe heat exchangers that are cast into concrete storage elements. These elements are specially designed to deal with thermal deformations and stressing. The flow through the modular system is typically arranged in parallel and serial fashion. A NEST TES is fully scalable and may consist of thousands of storage elements compactly arranged within an insulated building. The scalability implies that there is virtually no limit to size; for instance, an installation may have storage capacity for several GWh_{th}. Thermal oil, pressurized water/steam, or compressed gases may be used as HTF. The storage is suited for high temperature applications up to 550°C for electric power generation as well as moderate temperature applications such as process heat down to 100°C. The storage is well suited for concentrated solar power (CSP) and other applications with direct generation of heat. The storage can equally well be used for storing “surplus” electricity, converted to heat, in areas with high penetration of variable renewable energy sources such as wind energy and/or photovoltaic. The first pilot plant will be built at the solar energy research facility at Masdar Institute in Abu Dhabi this year.

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Keywords: Thermal energy storage; solar energy; concrete; large scale

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1. Introduction

The formidable growth of renewable energy has ushered in a new set of challenges for real time matching of electric power generation to market demand. Renewable energy sources such as solar and wind are inherently intermittent. Clearly solar energy is unattainable after sunset and varies according to moving clouds and rain. Similarly, the output from wind turbines is zero at times with no wind or too strong wind and it fluctuates strongly with the natural variation of wind speed. Ambitious political targets for renewable energy to be implemented over the coming years is expected to cause immense challenges in meeting real time electricity demand with supply and in balancing the electric power system in general.

Development of high capacity transmission grids (often termed “super grids”), integrating advanced communication technology and demand side management in the operation of the grid (often termed “smart-grid”) may mitigate circumstances, but will definitely not solve the underlying challenge. Large scale, long duration energy storage has emerged as a key enabling technology for the appropriation of renewable energy sources. Energy storage systems increase availability, flexibility, and dispatchability (capability of energy being released when needed). Unfortunately, current technologies for large-scale, long duration energy storage face severe limitations. Pumped hydro storage (PHS) and compressed air energy storage (CAES) require special topographical and geological conditions. Current battery technologies are very expensive and are most suitable for distributed load balancing. Hydrogen as an energy carrier is still imbued with technical challenges for storage in addition to high cost and low efficiency. Large scale high temperature thermal energy storage (TES) has until now been dealt with by molten salt storage, however this technology is somewhat restricted by relatively high cost, low scalability and risk of salt freezing at high temperatures. More information on energy storage in general can be found in [1].

Some new ideas for solid state TES will be outlined herein. This technology is currently under development and testing; whereas it already promises to have the potential for providing what renewable energy needs the most: effective, economical, and scalable energy storage. The current targeted application is concentrated solar power (CSP) whereas integration in other renewable energy applications will be tested in the future.

2. Thermal energy storage

2.1. Main principles

There are in principle three types of thermal energy storage: (1) sensible heat, (2) latent heat, (3) thermochemical. In the first case thermal energy is stored in a solid or liquid medium simply by transferring heat to that medium to increase its temperature (charging); this energy may later be drawn from the same medium when lowering the temperature (discharging). In the second case the stored energy is directly associated with the latent heat of phase transition, from solid to liquid or from liquid to gas. In the third case the stored energy is associated with reversible thermochemical reactions. The technology described herein is of the first type with sensible heat storage in a solid.

Fig. 1 shows a simple sketch of the principle of storing heat. Given a heat source such as the solar field in a CSP plant the heat may either be supplied directly to the heat sink (which could be a steam turbine, process or district heating application), or it may be transferred in part or as a whole to the TES. The stored heat may later, when needed, be discharged from the TES and used to maintain heat supply when heat is no longer available from the heat source. Heat is transported into the TES by way of a heat transfer fluid (HTF). The HTF could be for instance hot water/steam or thermal oil.

A more complete diagram will be described later. It should also be noted that the heat transferred to the storage may be sourced from electricity. This can simply be done by heating a HTF by Joule heating (electric resistance) and by pumping this heated fluid through the TES. Electricity may later, when needed, be regenerated by bringing heat from the TES into the power block. The energy loss of this reconversion is significant and dominated by the thermodynamics of the heat engine (typically steam turbine) which may be in the range of 30-45%. However, a TES may still be of great value when the purpose is to utilize surplus electric power from variable renewable energy sources and/or to ensure power system reliability. Moreover in a combined heat and power (CHP) setting one may be able to achieve very high efficiency, up to 80-90%.

A similar concept with steel pipe heat exchangers cast into concrete was developed and tested by the German Aerospace Center (DLR) during the 2000's. Results from these tests are reported in [2,3,4]. Compared to DLR's system, NEST's technology has clear advantages with respect to structural integrity of the solid state TES medium, and also much smaller footprint which reduces the heat losses. Moreover the specialized concrete developed by NEST and Heidelberg Cement described later, has significantly higher thermal conductivity, a key performance indicator. The properties of the TES medium are very important in achieving a cost-effective, high efficiency solid state TES system.

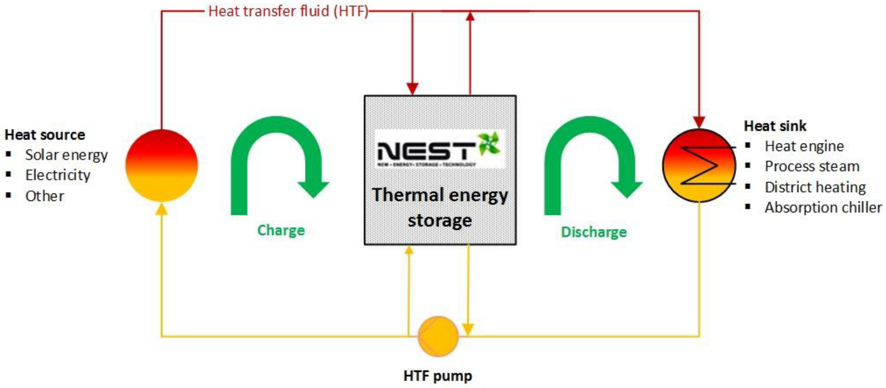


Fig. 1. Principle for thermal energy storage

2.2. Other TES technologies

Ancient societies knew how to make use of storing heat in stone; in particular storage was used for floor heating purposes. Also early industrial societies knew the importance of making more efficient use of energy by building heat storage. Today many districts have central heating systems with hot water storage and heat distribution. Clearly hot water has its limitations as TES medium because the boiling pressure increases rapidly with temperature.

More advanced ways of storing heat have been developed over the years, for instance chemical industry started making use of high temperature TES by way of molten salt several decades ago. Molten salt was installed commercially in a CSP plant for the first time in the late 2000's and now dominates the market for TES in CSP. Although this method has been proven to work well, molten salt is still rather expensive, especially for small and moderate size systems, and prone to risk of freezing at high temperatures when cooled.

The first CSP plant in the world – SEGS I in the US – was designed with a TES system based on thermal oil (the same oil used as HTF in the plant). Unfortunately, thermal oils are very expensive and require pressure vessels for storage at temperatures of more than 340°C. Steam accumulators have been installed as short term buffer storage in several direct steam CSP plants, however they supply only saturated steam and the technology is very expensive and not suitable for large scale storage. Latent heat storage systems using various salt compounds as phase change material (PCM) are currently being developed and may in combination with sensible heat storage such as that being developed by NEST provide an efficient, scalable and cost effective TES solution for direct steam CSP plants. Such CSP plants generate steam directly in the solar field, thus omitting the need for additional (expensive) HTF system and heat exchangers.

3. NEST storage technology

3.1. Thermal storage element

The addressed challenge is to develop an energy storage solution that can be built at almost any scale and that does not make use of expensive, rare earth materials. Clearly "rock" is an inexpensive and easily available material;

it can be shaped into almost any form and size by binding rock aggregates in the form of concrete. One obvious problem is that transferring heat to and from a solid state material may lead to significant thermal stress gradients that may cause cracking and damage the material which in turn may hamper the ability to transfer heat. Having a smart design that can deal with rapid heat transfer at very large scale is thus the key to solving this problem.

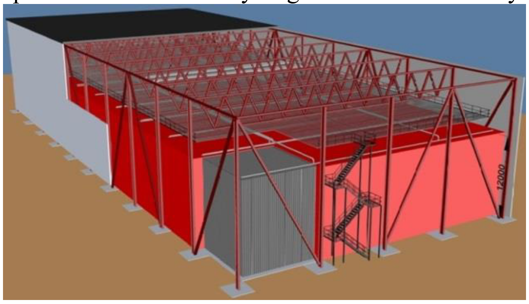


Fig. 2. Illustration of large scale NEST TES system.

In the NEST design the heat is transported to and from the TES using a HTF which flows through steel pipe heat exchangers cast into the concrete. The TES is made up of a multiplicity of similar storage elements; the number of which decides the overall heat storage capacity. Each element is made such that the heat transport distance through concrete will be consistent with the specified time for charging and discharging in the given application. The design ensures that thermal stresses will be minimized; further, there is a reinforcement system that reduces the risk of thermal cracking. Notably there is no direct contact between the fluid and the concrete; the heat transfer goes through heat exchanger walls made of steel.

3.2. Modular storage

NEST TES systems can be configured and sized according to the specific application of use. Typically the storage elements are vertical columns standing on a floor lab. The elements may be connected and arranged in a parallel and serial manner with respect to the way the HTF flows through these elements.

Fig. 2 shows an illustration of large scale NEST TES. Thousands of storage elements are arranged within a large building. A piping and valve system with active control determines the flow of HTF through the system during charging and discharging. The floor, walls and roof have an adequate layer of thermal insulation such that the total heat loss will be less than 1% during 24 hours.

It is worth noting that this type of TES may be placed almost anywhere; it may be in a city, an industrial area, or located off-shore. It can also be placed partly or fully in a structure below ground such that the space above may be used for other purposes.

4. Applications

4.1. Application areas

TES may in principle be used in many energy storage contexts; it is believed that the current technology may have a particularly wide range of applications. Some examples of where it can be used are:

- Concentrated solar power (CSP), which has a wide range of applications including generation of electricity, desalination of salt water, enhanced oil recovery, mining operations, and other industrial or residential heat applications.
- Electric thermal energy storage (E-TES) in power systems with high penetration of variable renewable energy sources such as wind energy or solar photovoltaic (PV).
- Thermal power plants
- Industrial heat

4.2. Concentrated solar power

There are two main types of solar power generation: (1) photovoltaic (PV) and (2) concentrated solar power (CSP). The research and development has so far been focused towards CSP.

In most CSP installations the radiation from the sun is concentrated to heat synthetic organic oil. This oil can be heated up under pressure to almost 400°C. The high temperature oil transfers its heat to generate superheated steam for a steam turbine generator that produces electricity. The TES can be connected in parallel with the solar field. Excess heat from the solar field during the day is stored in the TES and can be released when the sun sets to maintain electricity production. Depending on the size of the solar field and the TES relative to the steam turbine, and the operational strategy, the CSP plant can operate as a peak power plant, mid merit plant or even base load plant. A simplified illustration of a CSP plant with NEST TES is shown in Fig. 3.

The NEST system has been modelled in Matlab-Simulink with a fluid structure interaction model based on the finite element method. Fig. 4 shows simulation results for a 24 hour storage cycle using thermal properties of the concrete determined by laboratory experiments (described in section 5). The TES starts to discharge in the early morning (at t=14400) to start up the steam turbine and produce electricity during the morning peak load period, before there is sufficient heat available from the solar field. The TES is subsequently "empty" once the heat supplied from the solar field reaches the rated capacity of the steam turbine (at t=27000). The TES starts to charge once the heat from solar field is higher than the rated turbine capacity (at t=28800) and lasts until the TES is "full" (at t=54000). Discharging commences when the heat from the solar field drops below the rated capacity of the turbine (at t=64800) and heat from the TES maintains electricity production for several hours after sunset. The late evening discharge is typically of high value due to high electricity demand and peak prices in the market.

In this case the TES is designed with two temperature zones (hot, and intermediate/cold) to allow control of the discharge temperature. This enables a temperature ramp up in the morning and a steady outlet temperature during the late evening discharge. The outlet temperature appears to be quite volatile in Fig. 4 but this is due to simulation time step of 30 min for altering valve settings. In reality the temperature curve would be smooth due to continuous control of the regulating valves.

A NEST TES rated at 1.25 GWh_{th} could maintain close to full capacity of a 110 MW_{el} (gross) steam turbine for 4.5 hours. It may in addition provide lower temperature heat to start up the steam turbine in the morning and prolong electricity production at lower capacity by a deeper discharge of the TES. On days with good sun conditions there is often more than sufficient energy available from the solar field to fully charge the TES after a deep discharge, as shown in Fig. 4. For the simulated 24 hour cycle the TES can actually store 1.65 GWh_{th}. Table 1 lists the main features of this TES. As a comparison, a two-tank molten salt TES with a storage capacity of 1.25 GWh_{th} would require approximately 36.000 tons of molten salt (eutectic mixture of $NaNO_3$ and KNO_3).

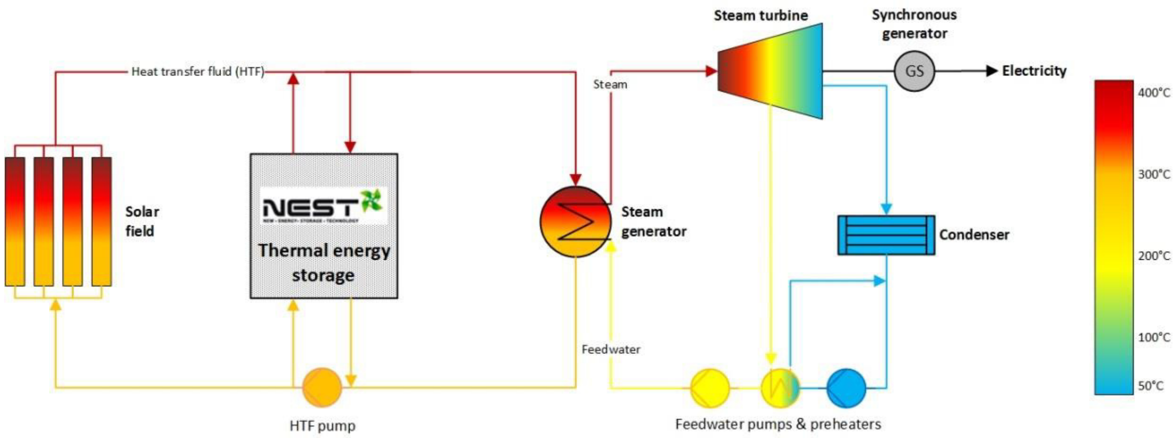
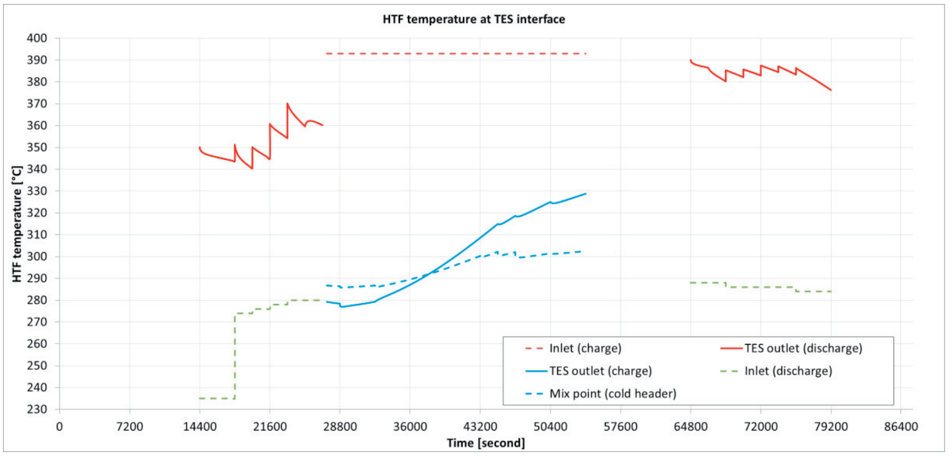


Fig. 3. Integration of TES in CSP plant with synthetic oil as HTF.



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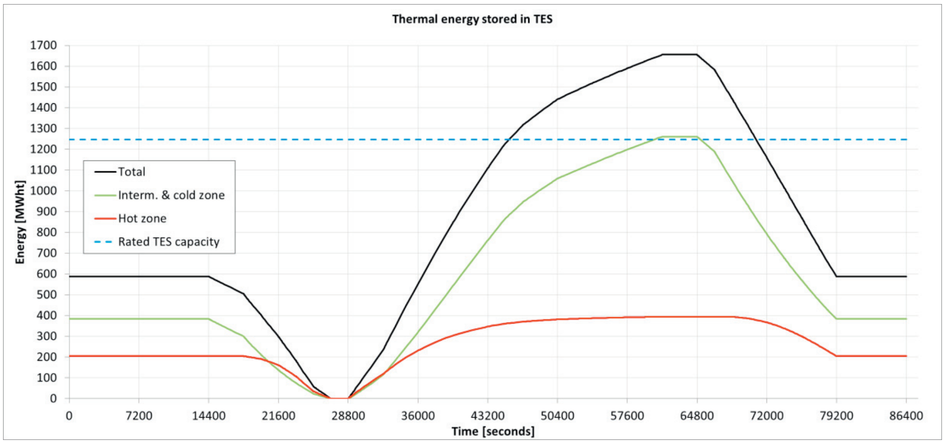

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Fig. 4. (a) Oil outlet temperature from TES; (b) Thermal energy stored in TES.

Table 1. Main features of large scale NEST TES for CSP plant with thermal oil as HTF.

Description	Value
Rated / maximum energy storage capacity	1.25 GWh_{th} / 1.65 GWh_{th}
Rated thermal power capacity	280 MW_{th}
Volume / mass of storage medium (Heatcrete®)	30 800 m^3 / 67 700 ton
Footprint	4 400 m^2
Height	14 m
Procurement and construction cost estimate	USD 50 million

5. Development and testing of the technology

5.1. Laboratory testing

The development of the solid state TES material has been ongoing since 2012; this work is done in close cooperation with Heidelberg Cement in Germany. All parameters relevant to the performance of the material have been investigated; the result of this is a concrete recipe that in total provides the best thermal properties, makes only use of readily available rock materials, the concrete can be easily mixed and placed in forms, it is suitable for transportation, and it has good cost performance. As part of this study a large number of laboratory specimen and element scale casting tests have been carried out. Clearly the key material parameters for solid state TES materials are thermal conductivity and heat capacity. Normal concretes have rather poor thermal conductivity; in fact, in most applications such as in buildings one would like concrete to be as thermally insulating as possible. For the current applications a special type of concrete with very high thermal conductivity at high temperatures has been developed. Since this particular concrete is used for heat applications rather than construction we have termed this material "Heatcrete®". Thermal conductivity and heat capacity for the full applicable range of temperatures has independently been verified by SP Technical Research Institute of Sweden. For the current version of Heatcrete®, at 340°C the thermal conductivity is about 2.2 W/mK and the specific heat capacity is 0.75 kWh/m^3K.

A following step with thermal testing of actual storage elements including two types of heat exchangers was carried out at the laboratories of Det Norske Veritas (now DNV-GL) at Høvik, Norway during fall 2013. These instrumented tests confirmed that the technology works well in practice at high temperatures. The storage elements that were subject to high temperature testing were cut in several places by sawing after the conclusion of the test phase. The cut surfaces confirmed that the concrete had retained its integrity without visible thermal cracks (Fig. 5).

5.2. Pilot at Masdar City, Abu Dhabi

NEST has signed an agreement with Masdar Institute in Abu Dhabi to build a pilot TES system at the solar research facility of the university in Masdar City. An experimental CSP technology referred to as "beam-down" has already been built there in 2011; this CSP facility is now being extensively upgraded with respect to carrying out more extensive research and development including the integration of a NEST TES pilot. It is to be noted that the particular design of the solar energy collection system consists of 45 mirrors on the ground that can rotate about two axes and that reflect the solar rays towards a matching number of mirrors in the tower. These fixed mirrors beam the rays down to the solar energy receiver at ground level. The receiver carries synthetic thermal oil equal to that used in commercial CSP plants. The facility has a nominal power of 100 kW_{th} and the maximum oil temperature is 400°C.

Fig. 6 (a) shows the ground based mirrors that automatically track the motion of the sun according to date and time. The central tower with mirrors is also shown in the picture; the platform holding these mirrors can be moved down for service if necessary. Fig. 6 (b) shows a simplified P&ID of the system as it will be after upgrading [5].

The NEST TES will be built to facilitate extensive research. The synthetic thermal oil will be heated by the beam-down CSP system or, alternatively, by the electric heater. The TES is currently under construction and it is planned to be finished during the fall of 2014. The TES will have a total storage capacity of 1.0 MWh_{th} and consist of 4 units enclosed and insulated within the same building. The TES has been designed and instrumented to accommodate many types of experiments in the future. Equally important, and since this is a first of its kind, successful operation of the pilot TES will represent the mile stone for future commercial use. Several commercial CSP projects with NEST TES technology are already in planning.

Fig. 5. Close view of NEST storage element after heating test at DNV-GL laboratory.

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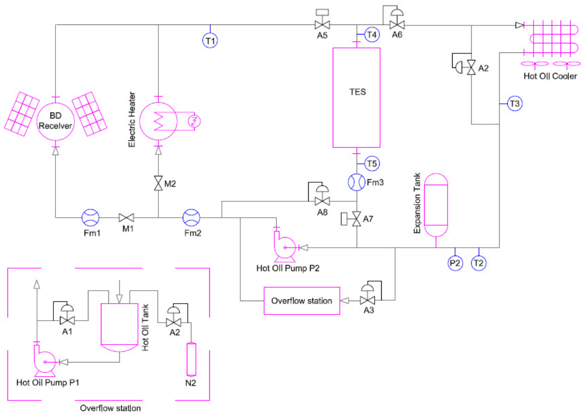
b 

Fig. 6. (a) Experimental beam down CSP facility at Masdar City; (b) Simplified P&ID including NEST TES [5].

6. Conclusions

This paper describes a new technology for storing energy in the form of heat in a special, relatively inexpensive solid state material. This proprietary technology is based on a series of innovative steps that makes heat transfer and thermal energy storage particularly efficient. Being able to operate at temperatures in the range of 300 – 500°C is the key to efficient generation electricity using steam turbines and electric generators. Equally important, this thermal energy storage technology is fully scalable to almost unlimited degree and can be installed almost anywhere. As a result of three years of research and laboratory testing a pilot thermal energy storage is now being built at the solar energy research facility at Masdar Institute in Abu Dhabi. Extensive testing and verification of all aspects of performance will be carried out during coming months and years. This energy storage technology has a particular relevance and importance for enabling high penetration of renewable energy in the overall energy mix since it can provide better reliability and overall utilization of renewable energy. When fully tested and "proven" it has a potential for making a great impact in the future energy industry.

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